Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System

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LONG-TERM GOAL

The long-term goal of this project is to improve our capability to predict the inherent spatial and temporal variability near the Philippine Straits, and thus contribute to the development of reliable prediction systems.

OBJECTIVES

The primary focus is to provide a comprehensive understanding of the remote and local factors that control the meso- and submesoscale features in and around the Philippine Archipelago Straits. The main objectives are:

- to explore the effects on the Philippine Straits of remote forcing from the equatorial waveguides, throughflows, and adjacent seas mesoscale dynamics;
- to estimate the effects of local winds in generating meso- and submesoscale variability;
- to quantify the role of barotropic tidal forcing in promoting side wall eddies and internal tides;
- to study the role of abrupt changes in bathymetry in generating submesoscale variability; and
- to investigate the impact of variational data assimilation on the simulation and predictability of the meso- and submesoscale circulation features.

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APPROACH

The approach for achieving the proposed goal and objectives is via model simulations using ROMS (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009) and its comprehensive ocean prediction and analysis system (Moore *et al*., 2004, 2009, 2011a,b,c). Tidal forcing is imposed using available global OTPS model.

ROMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski *et al*., 2004; Warner *et al*., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom. Several adjoint-based algorithms exists for 4-Dimensional Variational (4D-Var) data assimilation (Moore *et al*., 2011a,b,c; Powell *et al*. 2008; Muccino *et al*., 2008; Di Lorenzo *et al*., 2007), ensemble prediction, adaptive sampling, circulation stability (Moore *et al*., 2004), and sensitivity analysis (Moore *et al*., 2009).

Two regional, nested grids have been built: coarse (5 km), and fine (2 km). The initial and lateral boundary conditions are from the 1/12° global HYCOM with NCODA (provided by Joe Metzger and Harley Hurlburt) and 1/4° global Mercator with data assimilation (ORCALIM025), atmospheric forcing is from NOGAPS 3-hours, half-degree resolution, and the tidal forcing is from the global OTPS model.

WORK COMPLETED

Real-time forecasts without data assimilation in the Philippine Archipelago were carried out in support of the *Exploratory* cruise (June 2007), *Joint* cruise (December 2009), *Regional IOP-1* cruise (January 2008), and *Regional IOP-2* cruise (February-March 2009). Each prediction cycle, updated daily, was run for 9 days (4-day hindcast and 5-day forecast). The model was initialized 4 days prior to the forecast cycle starting day to use reanalyzed atmospheric and boundary forcing. Real-time forecasts can be found at http://www.myroms.org/philex.

A tidal harmonic analysis on free-surface and currents was carried out to validate and compare ROMS against OTPS fields. The results show that the barotropic tides are well simulated in ROMS except in the interior of the Philippine Archipelago for the 5km grid. This is improved in the 2km grid indicating that finer resolution is needed to resolve the inter-island passages. This analysis was also used to study the structure and generation mechanisms of internal tides. We found that internal tides are generated in the Sulu islands chain and propagate in both directions towards the Sulu Sea to the north and the Celebes Sea to the south (Zhang *et al.*, 2010).

As a preamble to the data assimilation experiments, optimal perturbations and adjoint sensitivity analysis were performed to identify the validity of the tangent linear approximation, assimilation time

windows, and observational operators. Three different adjoint sensitivity metrics have been computed for the Mindoro, Bohol, Surigao, and San Bernardino Straits. They are: transport, velocity anomaly, and temperature anomaly. Results indicate that bathymetry, temperature and velocity are crucial to obtaining a good estimate of transport.

RESULTS

Numerical modeling in the Philippine Archipelago is challenging for any global or regional ocean model due to the complex bathymetry, which includes numerous islands, passages, and several semi-enclosed basins and seas. In addition, developing a reliable, real-time nowcast/forecast system is a difficult task due to the lack of continuous surface and sub-surface observations that are needed for data assimilation. The satellite-derived data that is essential in any regional ocean prediction system is not that reliable in the Philippine Archipelago due to the frequency of clouds when deriving SST or the island geometry in the altimetry-derived SSH. Scientific, high quality blended multi-sensor (microwave and infrared; altimetry) products are not available for real-time forecasting because they are usually delayed by at least several days. Lower quality, near real-time products are available with a 1 to 2 day delay. The sub-surface observations needed to support and evaluate a regional ocean prediction system are scarce in both space and time. To illustrate this point, Figs. 1 and 2 show some of observations types that are available for data assimilation (Arango et al., 2011).

Figure 1a shows a daily map of sea level anomaly for June 6, 2007, at $1/3^{o}$ horizontal resolution from altimetry products produced by Ssalto/Duacs and distributed by Aviso. It is a merged product using all altimetry (Jason-1, Envisat, and GFO) measurements relative to the Mean Dynamic Topography (MDT) data estimated by Rio et al. (2005). Notice that data is only available in the Sulu Sea, Celebes Sea, South China Sea, and the Pacific Ocean to the east. This is due to the difficulty to process the altimetry data in the archipelago geometry with many islands and passages.

The hydrographic measurements from the PhilEx *Exploratory* Cruise (6 June – 3 July 2007) are shown in Fig. 1b. The station locations from R/V Melville (Gordon *et al.*, 2011) are marked with red symbols, the EM-APEX profiling floats trajectories near Panay and Mindoro islands (Girton et al., 2011) are marked with blue symbols, and glider measurements between Panay and Negros islands and near Surigao Strait are marked with green symbols. Notice that there are still large areas in need of sub-surface observations, and these data maybe important to support and evaluate an ocean prediction system for the Philippine Archipelago.

Fig. 1c shows the 2007 Argo floats observations obtained from the quality controlled UK Office Met Office EN3 dataset (Ingleby and Huddleston, 2007). The symbols are colored according to 2007 year-day. There are only few observations in the Sulu and Celebes Seas. Most of the observations are confined next to the Philippines Trench in the Pacific Ocean. Fig. 1d shows the 2007 XBT temperature profile locations from the UK Office Met Office EN3 dataset. Again, the time of the profiles is color coded by the year-day. Nearly all the profiles are located in the western Pacific Ocean.

Figure 2 shows a sample of the typical SST products that are available for assimilation in the Philippine Archipelago on June 6, 2007. Fig. 2a is an optimally interpolated (OI) SST at 10km horizontal resolution that blends the microwave (AMSR-E and TRMN) and infrared (MODIS) sensor data. The SST map is continuous and smooth because of the objective mapping statistical

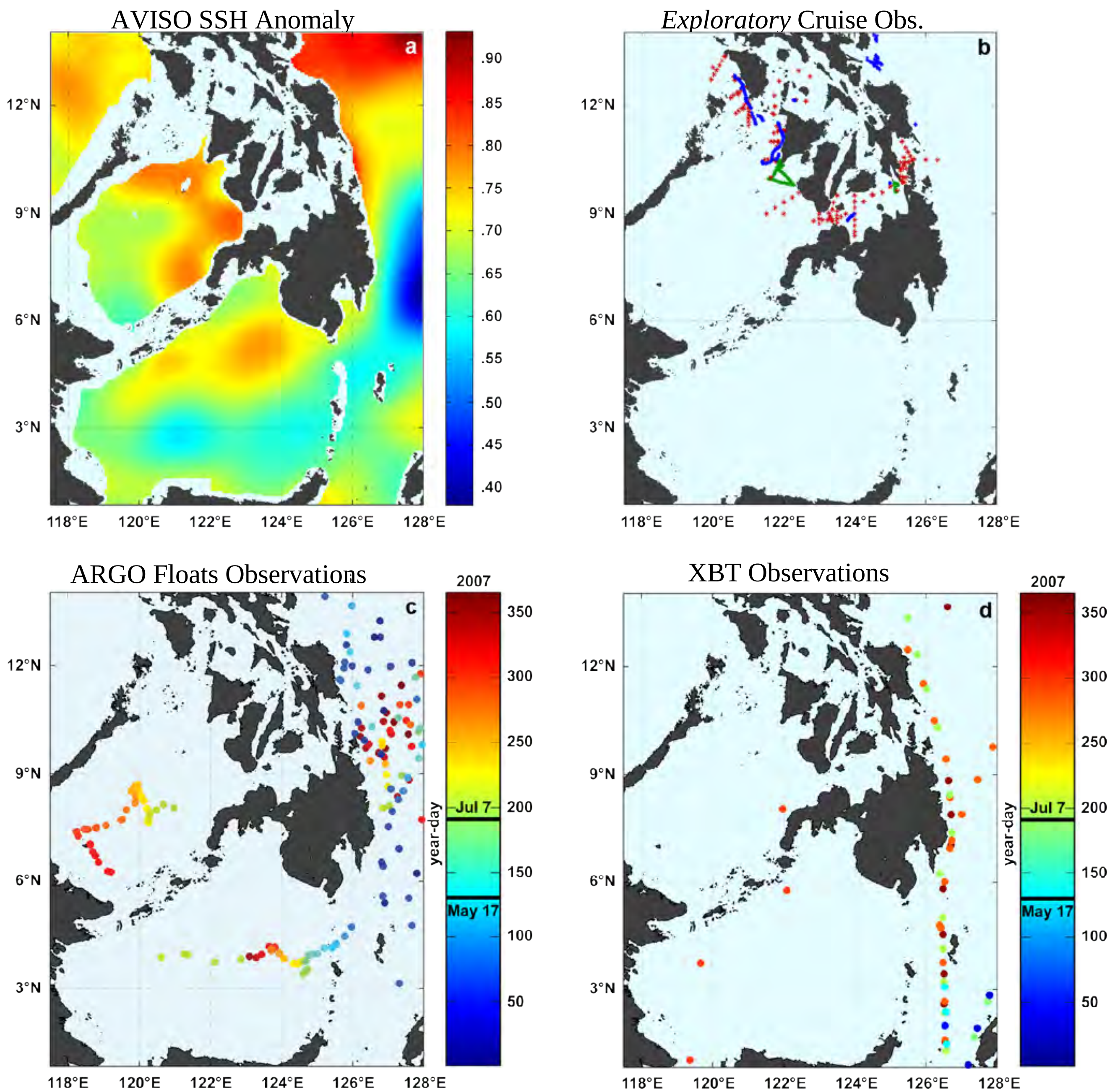

Figure 1: Observation datasets available for assimilation: a) sample of gridded, satellite-derived SSH anomaly from Aviso for 6 June 2007, b) Exploratory cruise track, 6 June – 3 July 2007, showing CTD stations (red), EM-APEX profiling floats trajectories (blue), and two glider tracks (green), c) Argo float profiles colored by 2007 year-day, and d) XBT temperature profiles colored by 2007 year-day.

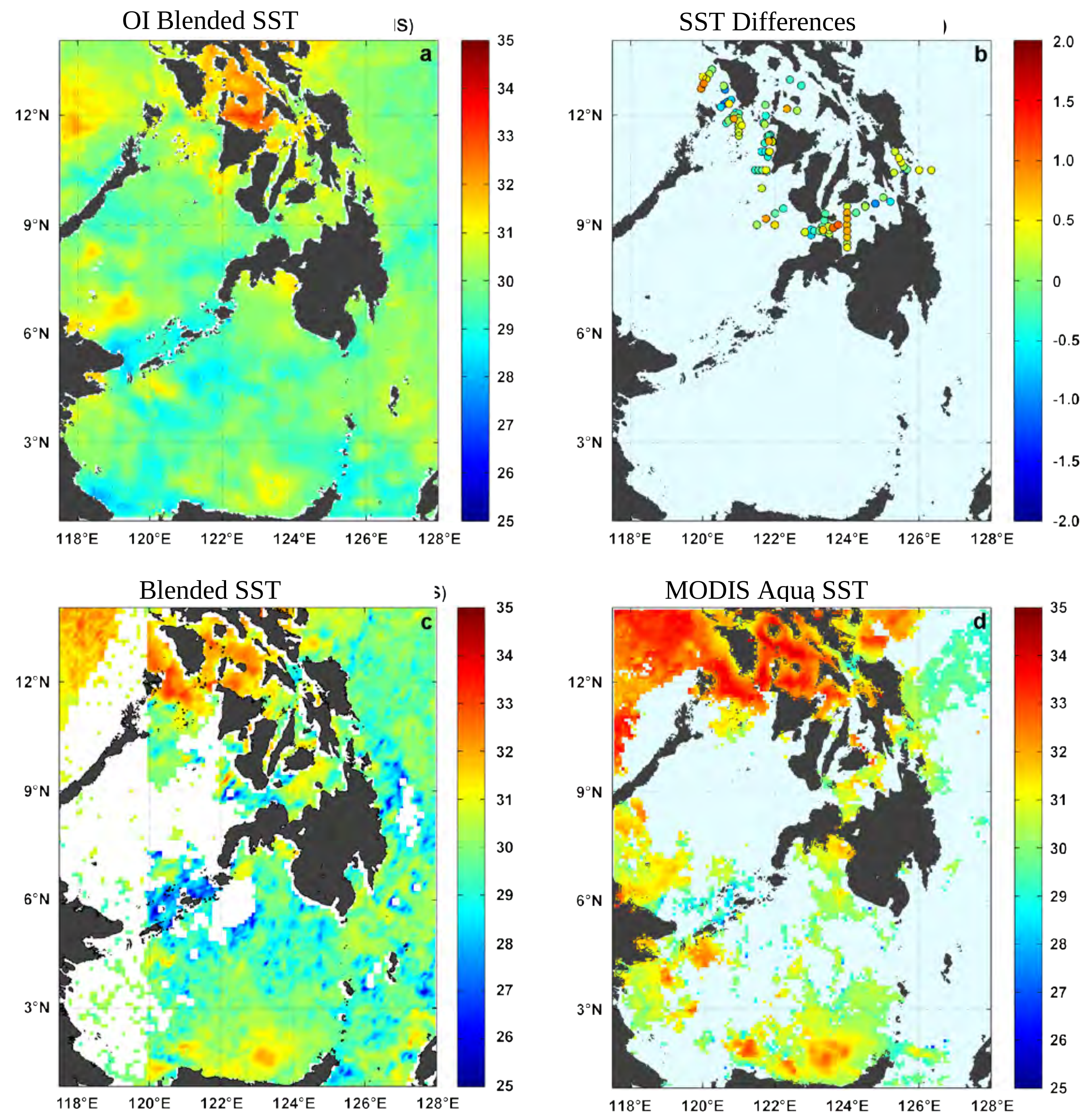

Figure 2: Sample of satellite-derived SST products for 6 Jun 2007: a) gridded OI SST blend from microwave (AMSR-E and TMI) and infrared (MODIS) sensors, b) SST difference (° C) between surface temperature from Exploratory cruise and OI SST product, c) experimental 5-day SST composite using data from microwave (AMSR-E) and infrared (MODIS, AVHRR, POES, GOES) sensors, and d) SST from MODIS.

assumptions. The gaps in the data due to clouds are filled with the first guess values (climatology and/or previous analysis) during the objective mapping. A data comparison of this SST product against surface temperatures measured during the *Exploratory* cruise is shown in Fig. 2b and gives a RMSE of 0.5^{o} C. The colored circles in Fig. 1b indicate the cruise track. An experimental 5-day composite SST

is shown in Fig. 2c at a 0.1 ^{o} horizontal resolution derived from microwave and infrared sensors aboard multiple platforms (AMSR-E, AVHRR, GOES, MODIS). No attempt is made to objectively analyze the blended SST product, as in Fig 1a. Notice the lack of data in the Sulu Sea and warmer SST along Mindoro. This indicates that the first guess for the OI in Fig. 2a is older than 5-days and the values have been persisted to create a complete map without gaps. Finally, Fig. 2d shows an infrared image from the MODIS sensor. This map illustrates the frequent obscuring effects by clouds in the Philippine Archipelago. The SST is much warmer than the other products yielding a 0.75 ^{o} C RMSE when compared with the cruise data.

The available data was assimilated using ROMS I4d-Var algorithm described in Moore et al. (2011a). Fig. 3 shows the temperature and salinity RMSE between model and observations along the cruise track from 6-24 June 2007. The blue curve shows the values for the non-assimilative real-time control forecast, while the red curve shows the values of the daily nowcasts resulting from the I4D-Var minimization between model and observations for the previous 5 days. The black curve shows the values of the nonlinear model run in hindcast mode and initialized from the nowcast during the verification step without data assimilation. It should be noted that the error in the nowcast is based on the observations that have been used during I4D-Var estimation. It is a measure of how close the model is getting to the observations. On the contrary, the error in the hindcast run is computed with observations that have not yet been assimilated. It can be seen in Fig. 3a that the temperature correction is between 1.0° and 2.0° C. The correction for salinity (Fig. 3b) is also significant, at nearly 0.2. Most noticeably, the forecast initialized from the nowcast (black curve) has better skill than the non-assimilative, real-time control run (blue curve), especially for salinity. The larger salinity correction is primarily due to correcting the excessive salt flux through the lateral boundaries and for uncertainties in the surface freshwater flux (evaporation minus precipitation) in the control forecast.

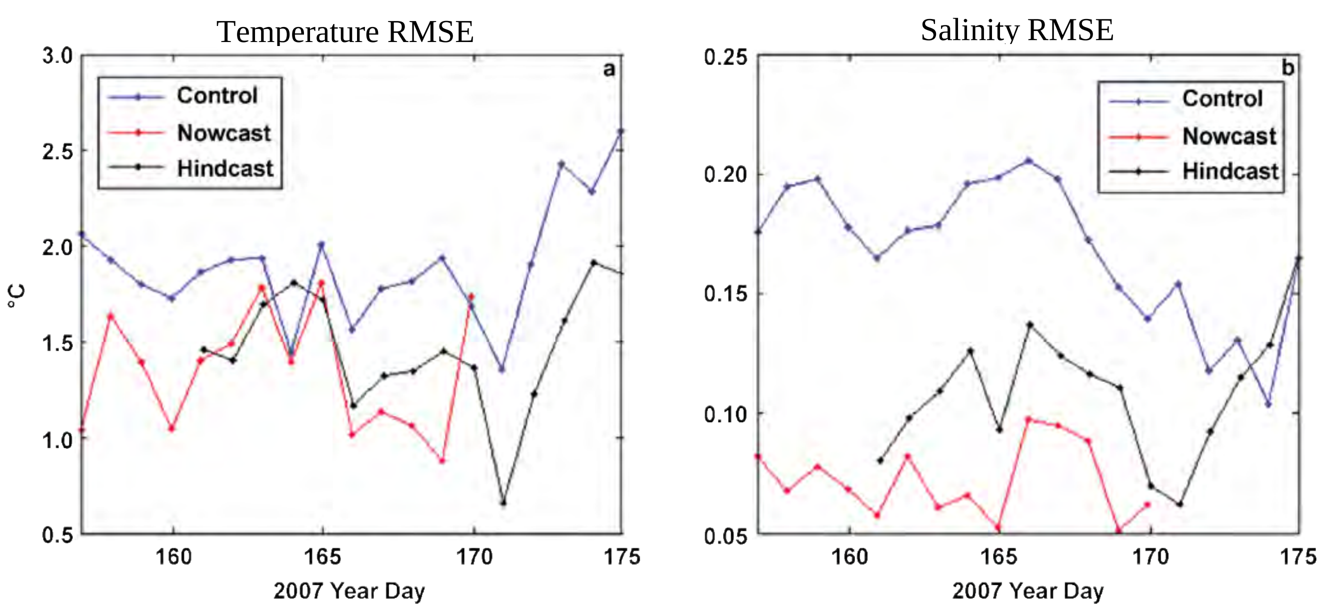

Figure 3: RMSE between model and observation for the real-time control forecast without data assimilation (blue curve), I4D-Var best estimate (nowcast) using observations from previous 5 days (red curve), and nonlinear model verification run in hindcast mode and initialized from the I4D-Var nowcast: a) temperature (^{o} C), and b) salinity.

Acronyms:

AMSR-E:	Advanced Microwave Scanning Radiometer for Earth Observing System
AVHRR:	Advanced Very-High Resolution Radiometers
MODIS:	Moderate resolution Imaging Spectrometers
NASA:	National Aeronautics and Space Administration
NOAA:	National Oceanographic and Atmospheric Administration
POES:	Polar-orbiting Operational Environmental Satellites (NOAA)
GOES:	Geostationary Operational Environmental Satellites (NOAA)
RMSE:	Root Mean Square Error
SST:	Sea Surface Temperature
SSH:	Sea Surface Height
TMI:	TRMN Microwave Imager
TRMN:	Tropical Rainfall Measuring Mission (NASA's spacecraft)

IMPACT/APPLICATIONS

This project will advance our scientific understanding of the generation dynamics and predictability of meso- and sub-mesoscale eddies near straits.

TRANSITIONS

None.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (Arango) closely collaborates with A. Moore (data assimilation and adjoint-based algorithms) at University of California, Santa Cruz, B. Powell (data assimilation applications) at University of Hawaii at Manoa, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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